REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED July 1, 1997 - August 31, 2000
4. TITLE AND SUBTITLE Decentralized Dynamic Decision Making and Its Applications to Wireless Communications		5. FUNDING NUMBERS 6-N00014-97-1-0823
6. AUTHOR(S) Venugopal Veeravalli		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Cornell University, 120 Day Hall Ithaca NY 14853		8. PERFORMING ORGANIZATION REPORT NUMBER OSP # 31683
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

14. SUBJECT TERMS	15. NUMBER OF PAGES 4
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT **UNCLASSIFIED**	18. SECURITY CLASSIFICATION ON THIS PAGE **UNCLASSIFIED**	19. SECURITY CLASSIFICATION OF ABSTRACT **UNCLASSIFIED**	20. LIMITATION OF ABSTRACT **UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Enclosure 1

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Final Report for ONR Grant N00014-97-1-0823

Decentralized Dynamic Decision Making and it Applications to Wireless Communications

PI: Venugopal Veeravalli

Project Activities (major research and education activities)

The work on ONR Grant N00014-97-1-0823 was performed during the period from July 1, 1997 through August 31, 2000, when the PI was an assistant professor at Cornell University. The research contributions were in three areas: (i) the solution to the problem of decentralized quickest change detection that has applications in wireless sensor networks, (ii) the design of adaptive hard handoff algorithms based on the locally optimal approach, (iii) the development of locally optimal soft handoff algorithms, and (iv) the development of optimal dynamic power control algorithms for CDMA systems.

The research funding was used primarily to partially support the M.S. and Ph.D. thesis work of Rajat Prakash, and to partially support the M.S. thesis work of Jean-Francois Chamberland.

Furthermore, the results derived in the course of this project were incorporated into two graduate-level courses at Cornell. One course, EE 564: Decision Making and Estimation, included some theoretical results on sequential hypothesis testing and change detection, and applications in sensor fusion. The other course, EE 568: Mobile Communication Systems, included a discussion of handoff and power control algorithms for cellular systems.

Project Findings (major findings from activities)

Decentralized Quickest Change Detection

We studied a decentralized formulation of the quickest change detection problem, where the distributions of the observations at all of the sensors in the system change at the time of disruption, and the sensors communicate with a common fusion center. An obvious application is in surveillance systems with multiple acoustic/optical sensors, where the sensor observations regarding the appearance of a target need to be fused at a fusion center.

We considered a Bayesian setting in which *a priori* knowledge of the change time distribution is available. The observations were assumed to be independent from sensor to sensor, conditioned on the change hypothesis. We derived an optimal solution to the problem under a quasiclassical information structure, where each sensor retains only its messages from the past (restricted local memory), and receives feedback from the fusion center about the past messages of the other sensors (full feedback). The solution has an elegant structure, where the sensors perform likelihood ratio tests with thresholds that depend on the *a posteriori* probability of the change taking place, and the fusion center performs a test similar to Shiryaev's original solution to the centralized Bayesian change detection problem. We also established a simple recursive procedure for the computation of the sufficient statistics at the sensors and at the fusion center.

To facilitate the implementation of the optimal solution, we developed an efficient technique for the numerical computation of the thresholds at the sensors and fusion center. We also extended the solution to the situation where *a priori* change time distribution information is not available. This was done by "uniformizing" the prior distribution.

The assumption of feedback from the fusion center, while simplifying the analysis is usually not valid in practice. Therefore, we used the structure of the optimal solution to arrive at a simple suboptimal policy that does not require any past message information. We also conducted a detailed numerical study in which we observed that the optimal solution offers little improvement over the suboptimal one, i.e., that feedback from the fusion center cannot be exploited to improve performance.

Details can be found in publications [B1], [J3], and [C6].

Adaptive Hard Handoff Algorithms

We have shown that it is possible to formulate the handoff problem as a stochastic control problem which can be solved using dynamic programming. Based on this formulation, we have developed a practical, locally optimal hard handoff algorithm, that is similar in complexity to the *ad hoc* hysteresis based tests that are currently in use, but outperforms them significantly. More importantly, we showed that the locally optimal test easily incorporates on-line estimates of system parameters such as velocity, and shadow fading variance so as to adapt to changes in these parameters.

The key to development of the locally optimal handoff algorithm was in the optimization of the tradeoff between link quality and rate of handoff. We defined adaptation precisely in terms of remaining on a locus of desirable operating points as system parameters (such as mobile velocity) change. We then used a linear cost criterion to select desirable operating points. For this rule, we showed that the optimal handoff algorithm, which is impractical, is easily adapted by fixing a single tradeoff parameter at an appropriate value. Surprisingly, the same adaptation property was shown to hold for the easily implementable locally optimal algorithm. This is in contrast to the poor adaptation of hysteresis based approaches which require look-up tables for adaptation. We also obtained practical estimators for all relevant system parameters based on a short window of pilot signal strength measurements. We showed that the locally optimal algorithm adapts well even when these simple estimators are used.

Details can be found in publications [J4], [C4], and [C5].

Local Optimal Soft Handoff Algorithms

We also worked on extending the locally optimal test to the soft handoff problem, where the mobile can be connected simultaneously to more than one base-station. Soft handoff is a feature of third generation cellular systems, based on the Code Division Multiple Access (CDMA) standard.

We posed the design problem is posed as a tradeoff between three metrics: the rate of handoffs, the mean size of the active set and the link quality. We first argued that the algorithm that optimizes the tradeoff between these metrics is impractical. We hence derived a Locally Optimal (LO) handoff algorithm as a practical approximation to the optimal handoff algorithm. We showed that the LO algorithm yields a significantly better tradeoff than the static threshold handoff algorithm used in second generation CDMA systems. We also showed that the dynamic threshold algorithm, which is an *ad hoc* algorithm proposed for third generation CDMA systems, achieves nearly the same performance as the LO algorithm. We hence established an analytical justification for the dynamic threshold algorithm.

Finally, we separated the handoff algorithm design into independent design problems on the forward and reverse links. We showed that the forward link LO algorithm is computationally intensive. However, we also established that this algorithm is closely approximated in performance by the simpler reverse link LO algorithm. Hence, the reverse link LO algorithm can be used on both links.

Details can be found in publications [J1] and [C3].

Optimal Dynamic Power Control for CDMA Systems

Our success with developing a theory for the handoff problem led us to believe that we can obtain similar results for other radio resource management problems. Among these, the power control problem is particularly interesting and challenging. Power control is especially important in CDMA systems, where users in the same cell can cause interference to each other. Much of the work on power control for cellular systems found in the literature focuses on static channel models, i.e., models in which the channel gain of every user is assumed constant. The performance results obtained under this assumption will be valid as long as the reaction time of the power control algorithm is small compared to the coherence time of the underlying wireless channel. In other words, the transmitted power of each user is implicitly assumed to converge to its optimal level before any significant change occurs in the channel state.

We considered the more interesting problem of designing dynamic power control algorithms for cellular CDMA systems. We posed the design problem as a tradeoff between the desire for users to maximize their individual capacity and the need to minimize the transmitted signal energy over the duration of their calls. Based on dynamic programming arguments, we derived an optimal multiuser solution. We showed that the multiuser solution decouples, and effectively converges to the single-user solution in the large system asymptote, where the number of users and the spreading factor both go to infinity with their ratio kept constant. The proposed solution for the large system is a simple decision rule that is easily implementable in practical third generation cellular CDMA stems.

Details can be found in publications [J2], [C1] and [C2].

Publications

Books and Book Chapters

[B1] A. G. Tartakovsky and V. V. Veeravalli. "Change-Point Detection in Multichannel and Distributed Systems With Applications." To be published in *Applied Sequential Methodologies: An Edited Volume.*

Journal Papers

[J1] R. Prakash and V. V. Veeravalli. "Locally Optimal Soft Handoff Algorithm." Accepted for publication in the *IEEE Transactions on Vehicular Technology.*

[J2] J.-F. Chamberland and V. V. Veeravalli. "Decentralized Dynamic Power Control for Cellular CDMA Systems." To appear in the *IEEE JSAC – Wireless Series* in 2002.

[J3] V. V. Veeravalli. "Decentralized Quickest Change Detection." *IEEE Transactions on Information Theory.* 47(4): 1657-65, May 2001.

[J4] R. Prakash and V. V. Veeravalli. "Adaptive Hard Handoff Algorithms." *IEEE Journal on Selected Areas in Communications - Wireless Communication Series.* 18(11): 2456 -2464, November 2000.

Conference Publications and Presentations

[C1] J.-F. Chamberland and V. V. Veeravalli. "Decentralized Dynamic Power Control for Cellular Spread Spectrum Systems." In Proc *ITCOM Conference on Modeling and Design of Wireless Networks* Denver, August 2001. (**Invited.**)

[C2] J.-F. Chamberland and V. V. Veeravalli. "Optimal Dynamic Power Control for CDMA Systems." In *Proc. ISIT 2000,* Sorrento, Italy, June 2000.

[C3] R. Prakash and V. V. Veeravalli. "Locally Optimal Soft Handoff Algorithm." *In Proc. IEEE VTC2000-Spring,* Tokyo, Japan, May 2000.

[C4] R. Prakash and V. V. Veeravalli. "Adaptive Hard Handoff Algorithms." *Proc. 1999 Vehicular Technology Conference,* Houston, TX, May 1999.

[C5] R. Prakash and V. V. Veeravalli. "Accurate Performance Analysis of Hard Handoff Algorithms." *Proc. 9th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC),* Boston, MA, September 1998.

[C6] V. V. Veeravalli. "Further Results on Decentralized Change Detection." *Proc. 1997 IEEE International Symposium on Information Theory,* Ulm, Germany, June-July, 1997.